Surface Texture Analysis of Nanostructures

Abstract

As electrical components become smaller and more condensed, nanotechnology is needed to create new and better materials for these components. The materials used in this research were Indium Gallium Arsenide and Aluminum Oxide made by Molecular Beam Epitaxy and Jet Vapor Deposition respectively. Several samples of each material were imaged using an Atomic Force Microscope (AFM) which shows the topography of a sample. The surface texture of these samples was the primary focus of this research. Generally, a smoother sample will have more desirable electrical properties than a rough sample. Using various parameters from the AFM and an image processing software ImageJ, our goal was to determine which parameters best portray the roughness of a sample. We found that standard deviation, inverse difference moment, and entropy portray roughness the best. This knowledge can aid future experiments that more directly involve the electrical properties of similar materials.

Introduction

Nanotechnology has become an extremely important aspect of electronics in recent years. As technology advances, electronics become smaller and smaller. As electrical components are scaled down, their effectiveness and their ability to be made easily, eventually decrease dramatically. New materials are needed that are more effective on a smaller scale and can be created efficiently. Nanotechnology is so important because it offers a solution to this problem. Nanotechnology, the study of things 10^{-9} times the length of a meter, allows a way to create potential new materials and allows analysis of their efficiency.

Two such materials were analyzed in this study: Indium Gallium Arsenide (InGaAs) and Aluminum Oxide (AlO). Both have the potential to replace current metals in electrical components. InGaAs has the potential to replace silicon in transistor channels. It is made through a process called Molecular Beam Epitaxy, which allows for fine control of impurities added to the compound. In this study, beryllium was added to samples. Beryllium increases the electrical properties of the material, but it also makes it rougher. Roughness can decrease a sample's usefulness because a smooth sample, which allows for easier electron flow, will tend to have more favorable electrical properties. The key is to add the optimal amount of beryllium to enhance electric properties without creating too rough a sample.

AlO has the potential to replace silicon dioxide as a gate dielectric. A gate dielectric is used in a transistor between the gate and substrate. Its purpose is to increase the capacitance between the two plates. The size, shape, and material of the gate dielectric correlate to its k-value, the factor by which it increases capacitance. A high k-constant refers to a high capacitance. As devices get smaller so do these dielectrics. Thinner gate dielectrics lose effectiveness because they have a lower dielectric strength. After a critical voltage electrons will begin to tunnel through the dielectric making it ineffective. This voltage is much lower for thin materials. New materials that can be thicker yet retain the same capacitance are required to prevent this tunneling. AlO, created through Jet Vapor Deposition, is one potential material that may solve this problem. Again, a smooth material is desired as it results in a higher k-constant. However, the variations of Aluminum Oxide can be created from differences in vapor speed and carrier gas.

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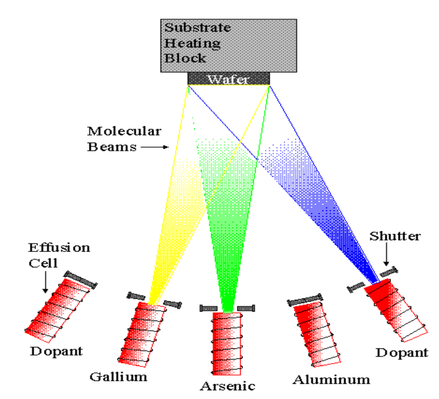
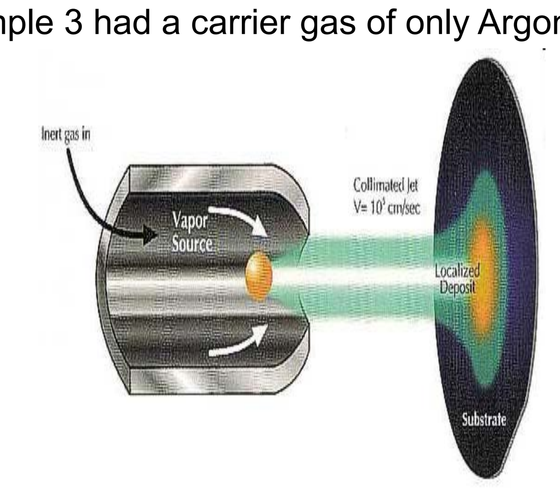
Methods

The first step in this experiment was to create the samples. This step was done by Dr. Larry Lee and Dr. T.P. Ma at Yale University. The Indium Gallium Arsenide samples were created using Molecular Beam Epitaxy (MBE). MBE creates a thin film on a substrate. Indium Phosphate was the substrate in this experiment. The specific elements being used are held in an effusion cell where they are evaporated and shot at the substrate as desired. In this experiment, beryllium was added to InGaAs samples at different temperatures to change the roughness and electrical properties of the sample. The higher the temperature, the more Beryllium and roughness was expected. The control sample was the Indium Phosphate substrate and should therefore be the smoothest. The four textured samples were InGaAs with the dopant Beryllium added at 794°C., 820°C., 840°C., and 860°C. respectively.

Jet Vapor Deposition (JVD) was used to create the Aluminum Oxide samples. JVD, like Molecular Beam Epitaxy, creates a thin film of a desired composition on a substrate, Silicon in this case. The desired elements are vaporized into an inert gas, the carrier gas, using a heated filament. The gas is then sprayed in a stream at high speeds, the stream velocity, towards the substrate. Our control was the Silicon substrate. The others were AlO created different ways. Sample 1 had a carrier gas combination of Argon and Nitrogen and a stream velocity of 400 Standard Cubic Centimeters per Minute (sccm). Sample 2 has the same carrier gas and a stream velocity of 300 sccm. Sample 3 had a carrier gas of only Argon and a stream velocity of 400 sccm.



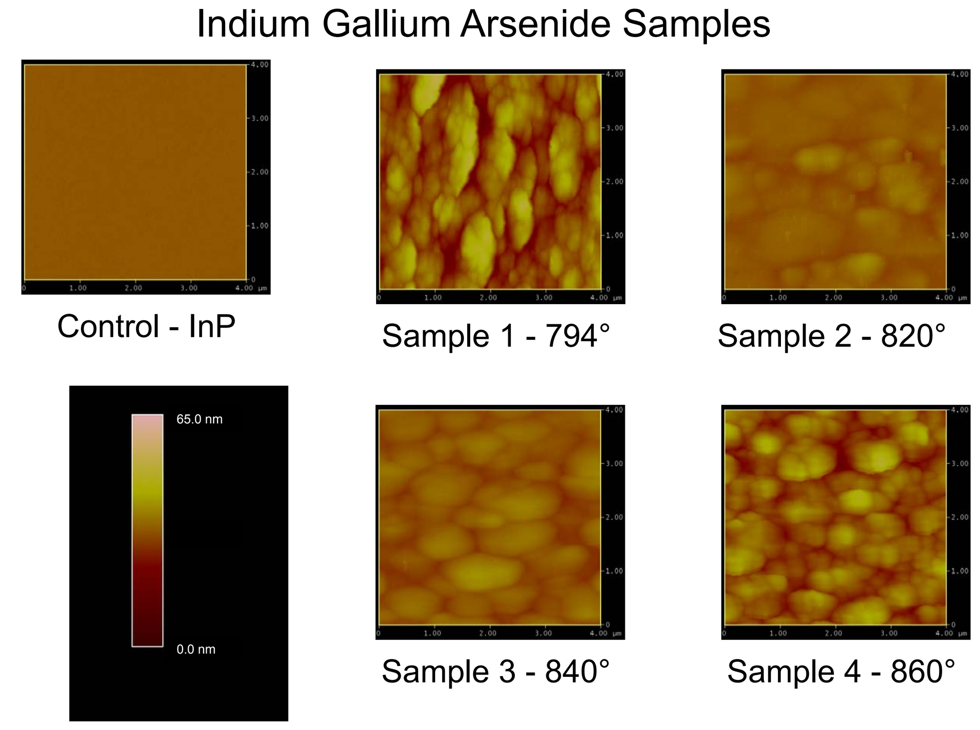
Molecular Beam Epitaxy



Jet Vapor Deposition

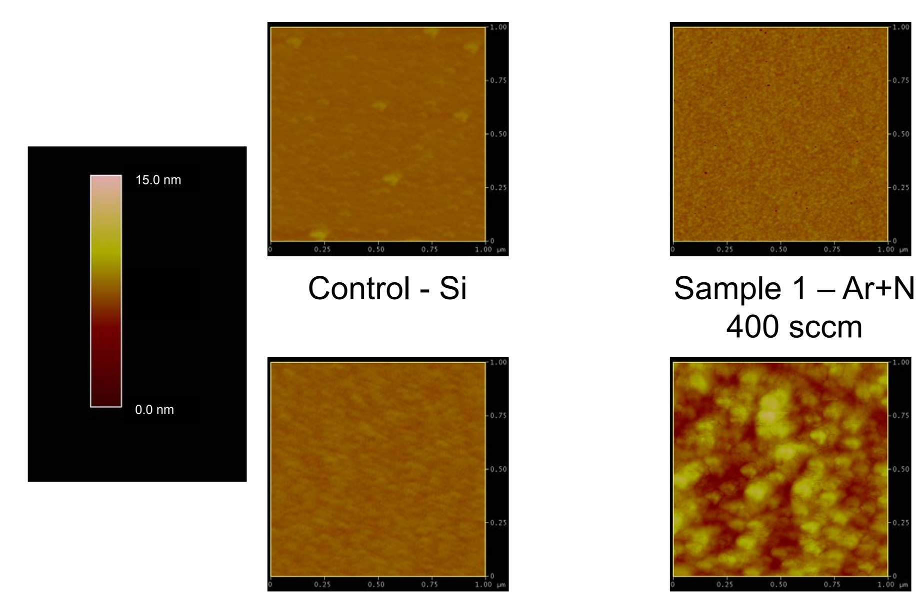
Next we imaged the samples using an atomic force microscope (AFM) in tapping mode. An AFM is ideal for this experiment because it maps the surface topography of a sample and therefore can be used to analyze surface roughness. Using a cantilever oscillating at a constant amplitude, the AFM measures the height of each point by utilizing the interactions between the tip of the cantilever and the sample. The computer records this height and uses it to make an image. Five images were taken in various places of each sample.

Indium Gallium Arsenide Samples



Control - InP; Sample 1 - 794°; Sample 2 - 820°; Sample 3 - 840°; Sample 4 - 860°

Aluminum Oxide Samples



Control - Si; Sample 1 – Ar+N 400 sccm; Sample 2 – Ar+N 300 sccm; Sample 3 – Ar 400 sccm

Lastly, we processed the images. Several parameters came from the AFM itself and were put into an excel spreadsheet. Then the image was cropped to the section showing the sample and grayscaled in an image processing program called ImageJ. An ImageJ plugin, Batch_Texture, gave several more parameters, some of which were in both a vertical and horizontal direction. These parameters were put into the excel spreadsheet and several types of statistical analysis were done.

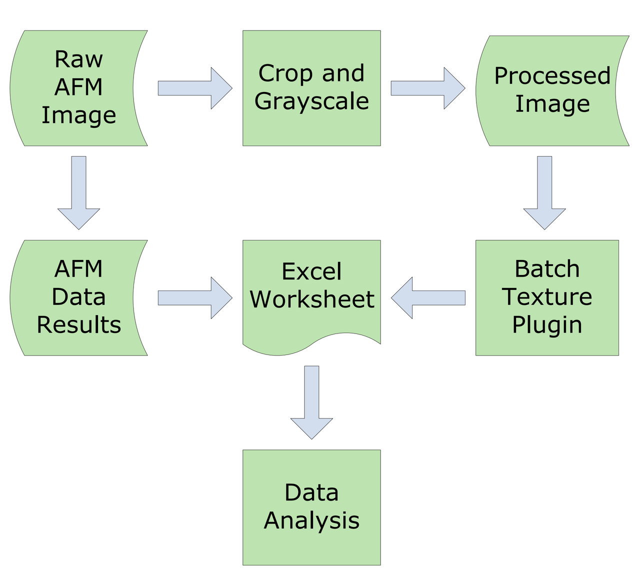
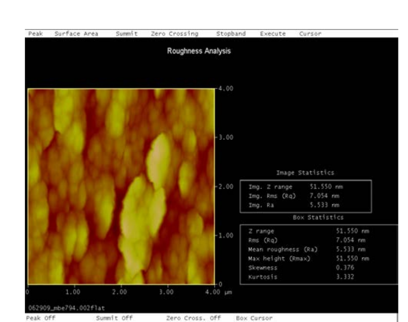
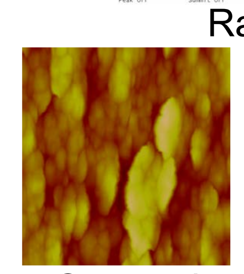


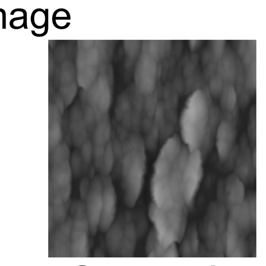
Image Processing Procedure



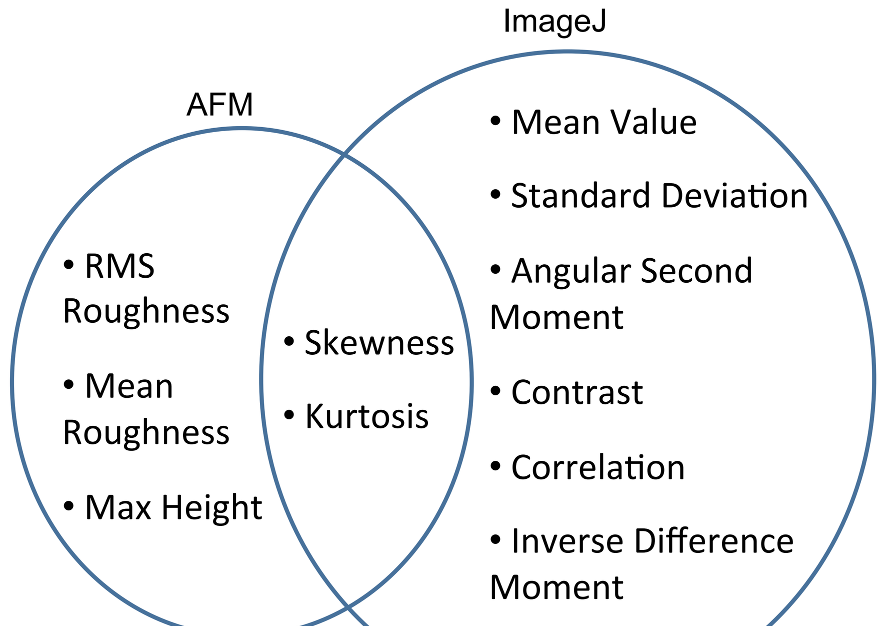
Raw Image



Cropped Image



Grayscale Image

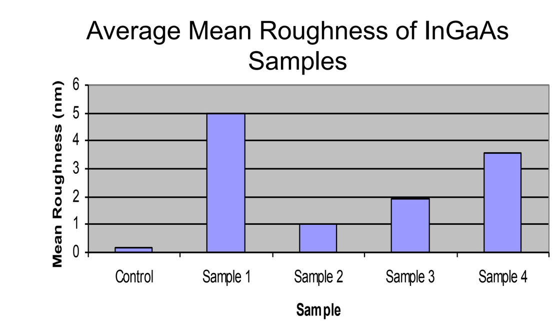


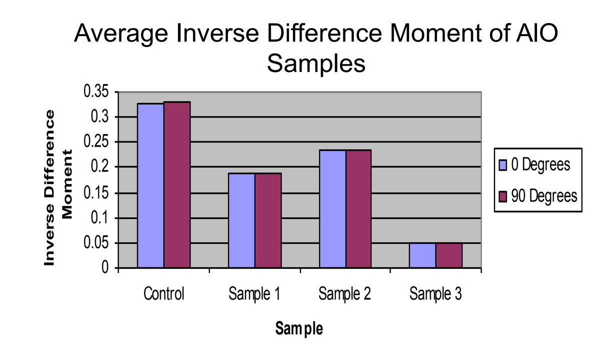
Parameters

Results

Even before processing, several things could be observed in the images. In the InGaAs samples, the control was clearly the smoothest, which was expected. After that Sample 2 seemed the smoothest followed by 3 and 4 and, lastly Sample 1. This seemed counterintuitive because Sample 1 had the least beryllium and therefore should be the smoothest of the textured samples. In the AlO samples, the control again seemed the smoothest. Sample 1 and 2 seemed about the same, while sample 3 looked clearly different. Changing the carrier gas obviously had a huge effect on surface texture.

Several statistical analysis techniques were used on the data to confirm the visual observations as well as to find the best parameters for measuring surface texture. A t-test for samples with unequal variance was used to find those parameters in which the mean of the control population was different than the mean of the textured population. Skewness and kurtosis are varied between the AFM and ImageJ, thus decreasing the confidence in these variables. Max height was deemed an insignificant parameter because it is set on the AFM.

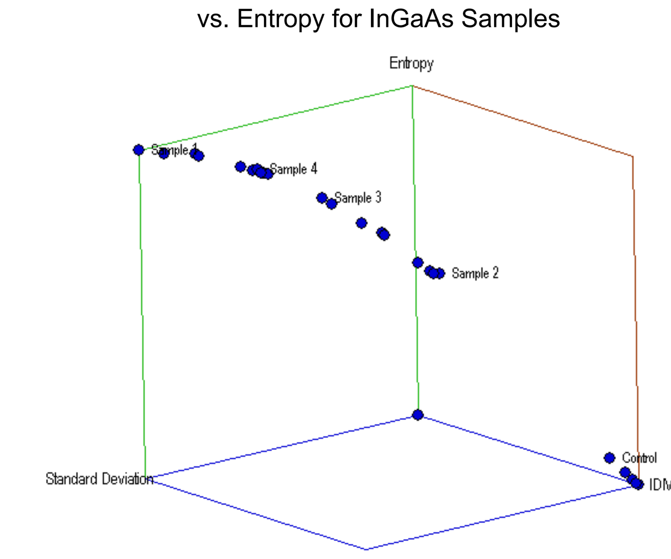




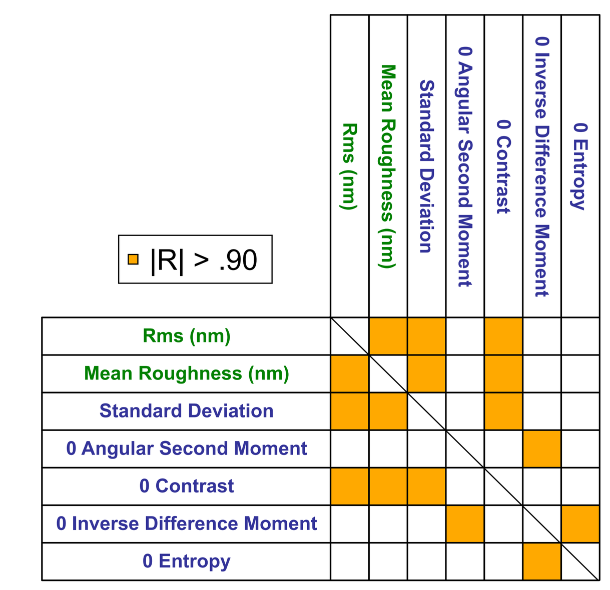
After we eliminated these parameters, we found the correlation value between each of remaining parameters. The 90° values of each parameter were eliminated as they were virtually equal to 0° value. Three groups of high correlation (>.9) remained. Rms roughness, mean roughness, standard deviation, and contrast were in one group. Inverse difference moment and angular second moment were in another. Entropy was alone.

Finally we used Excel to find the P Value for each of the remaining parameters. The lower the P Value the more confident we are that the control is significantly different from the textured samples. The parameter with the lowest P Value from each group was deemed the most accurate. These three parameters were mean roughness, inverse difference moment, and entropy. However, standard deviation and mean roughness had an extremely close P value, so standard deviation was selected as one of the best parameters for the sake of ease. This way, all three selected parameters can be found using ImageJ.

Standard Deviation vs. Inverse Difference Moment vs. Entropy for InGaAs Samples



Combined Correlation Chart



Conclusions and Future Research

Based on our results, the best parameters for determining surface texture are standard deviation, inverse difference moment, and entropy. However, several factors may have effected the results. Our small sample size forced us to use a somewhat qualitative approach to our statistical analysis. Other factors may have included substrate cleaning and outliers in the data.

Our work will allow researchers to analyze surface texture much more easily in the future. Once researchers have an image they will know exactly what parameters are the best for measuring roughness and how to measure them. However, future research must use similar samples prepared using MBE or JVD and imaged using an AFM to rely on our chosen parameters.

To show that our results are valid, further research must be done. Most importantly a larger sample size must be used, gathering many more images from multiples of each sample type. The types of materials used and how they are prepared must also vary in future research to assure that are results are universal and not just specific to our samples.

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